Functionally Designed Ultra-lightweight Carbon Fiber Reinforced Thermoplastic Composites Door Assembly

Project ID: mat118

DOE Vehicle Technologies Office Annual Merit Review, Online, June 21 - 23, 2022

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Overview

Timeline

- Start: December 1, 2015
- End: November 30, 2022
- 90 % Complete

Budget

- **Total project funding**
  - $2,249,994 (DOE)
  - $3,117,759 (Cost-share)
- **Funding for Budget Period 1 (12/1/2015 - 1/31/2017)**
  - $642,819 (DOE)
  - $871,357 (Actual Cost-share)
- **Funding for Budget Period 2 (2/1/2017 - 01/31/2018)**
  - $624,023 (DOE)
  - $674,889(Actual Cost-share)
- **Funding for Budget Period 3 (2/1/2018 - 01/31/2019)**
  - $643,239 (DOE)
  - $846,747(Actual Cost-share)
- **Funding for Budget Period 4 (2/1/2019 - 11/30/2022)**
  - $ 339,913 (DOE)
  - $ 773,906 (Actual Cost-share)

Barriers

- **Cost/Performance**
  - High cost of CFRP is the greatest barrier to the market viability of advanced composites for automotive lightweight applications.
  - Meeting CFRP-Thermoplastics performance to satisfy/exceed fit, function, crash and NVH at desired cost.
- **Predictive tools**
  - Integration of predictive models between systems (design/geometry/process/analysis) and at all length scales.

2017 USDRIVE MTT Roadmap report, section 5.1 and USDRIVE Partnership Plan, Goal 4, August 2020

Core-Partners

- Clemson University
- Honda North America
- Proper Tooling
- Lanxess
- University of Delaware

Relevance: Project Objectives

1. **Achieve a 50% weight reduction (USDRIVE Partnership Plan)**
   - Base weight = **31.8 kg**
   - Target Weight = **18.28 kg**

2. **Zero compromise on performance targets**
   - Similar crash performance
   - Similar durability and everyday use/misuse performance
   - Similar NVH performance

3. **Maximum cost induced is 5$ per pound saved**
   - Allowable increase = **$ 150.1 per door**

4. **Scalability**
   - Annual production of **20,000 vehicles**

5. **Recyclability**
   - European standards require at least **95 %** recyclability
   - Project goal is 100% recyclable (self imposed)

Milestones

- ✓ Establish design criteria (FY 2015-2016)
- ✓ Develop a detailed target catalogue (FY 2015-2016)
- ✓ Create a test and evaluation plan (FY 2015-2012)
- ✓ Benchmark the current door (FY 2015-2016)
- ✓ Test and catalogue commercially available materials (FY 2015-2016)
- ✓ Design and develop three functional door concepts that can meet project targets. (FY 2015-2016)
- ✓ Design optimization for non-linear load cases (Crash requirements) (FY 2017-2018)
- ✓ Down select design concept for concept detailing (FY 2016-2017)
- ✓ Design optimization for linear load cases (Use and misuse) (FY 2016-2018)
- ✓ Design optimization for non-linear load cases (Crash requirements) (FY 2018-2019)
- ✓ Fit and function testing with thermoset prototype door(FY 2018-2019)
- ✓ Sub-component testing (FY 2019 Q3)
- ✓ Final cost estimation (FY 2019 Q4)
- ✓ Design release for tooling (FY 2020 Q1)
- ✓ Tooling design completed (FY 2021 Q2)
- ✓ Tool manufacturing Completed (FY 2022 Q2)

COVID 19

- ⃠ Not Started - Prototype manufacturing (FY 2022 Q3)
- ⃠ Not Started - Final door crash testing (FY 2022 Q3)

Approach

Phase 1

Benchmarking & Target Definition


Frame **60% Reduction**


Window **20% Reduction**


Electronic **0% Reduction**


Trim **30% Reduction**
Or elimination

Baseline Door (This project) **31.1 kg**

Material Data Generation

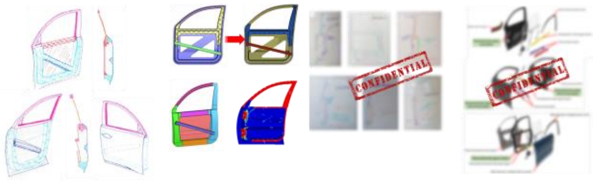
$$\begin{Bmatrix} f_1 \\ V_1 \\ M_1 \\ f_2 \\ V_2 \\ M_2 \end{Bmatrix} = \begin{bmatrix} \frac{AE}{L} & 0 & 0 & -\frac{AE}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{AE}{L} & 0 & 0 & \frac{AE}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \begin{Bmatrix} u_1 \\ v_1 \\ \theta_1 \\ u_2 \\ v_2 \\ \theta_2 \end{Bmatrix}$$

Mat 8 (Static Simulations)
MAT 54 (Dynamic Simulations)

Unidirectional PA 6 CF 50 wt %
Woven PA 6 CF 50 wt %

Phase 2

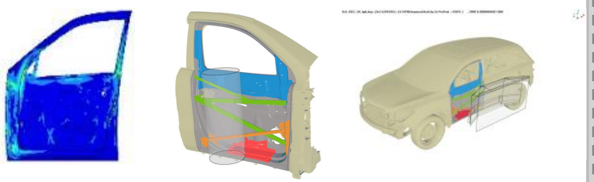
Concept Development



Extensive concept development
Systems level approach
Aggressive parts consolidation

Concepts developed **6 → 3 → 1**
Baseline Structural Parts **17**
ULCW Door Structural Parts **8**

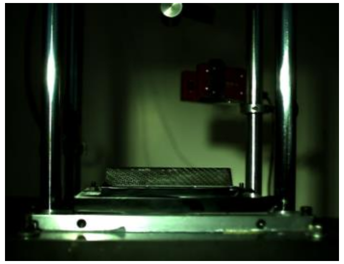
FEA Simulations



Door optimized for and passes
8 Static Cases
(Door sag, Sash rigidity …)
3 Dynamic cases
OEM requirement > FMVSS 214 targets

Phase 3

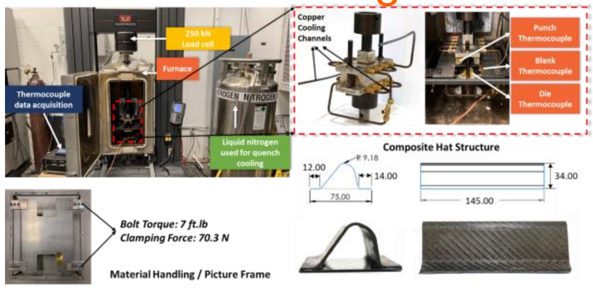
Subcomponent Testing



Calibrating and Validating MAT 54 Cards in Dynamic environment

Cost Analysis **Parametric cost model**
Fit and Finish **Low cost prototype fabricated (Passed)**

Thermoforming Trials



Developing a manufacturing to response pathway + Vendor selection (Lanxess)

Phase 4

Tooling + Prototyping


Leveraging experience of suppliers like Proper Tooling + Lanxess

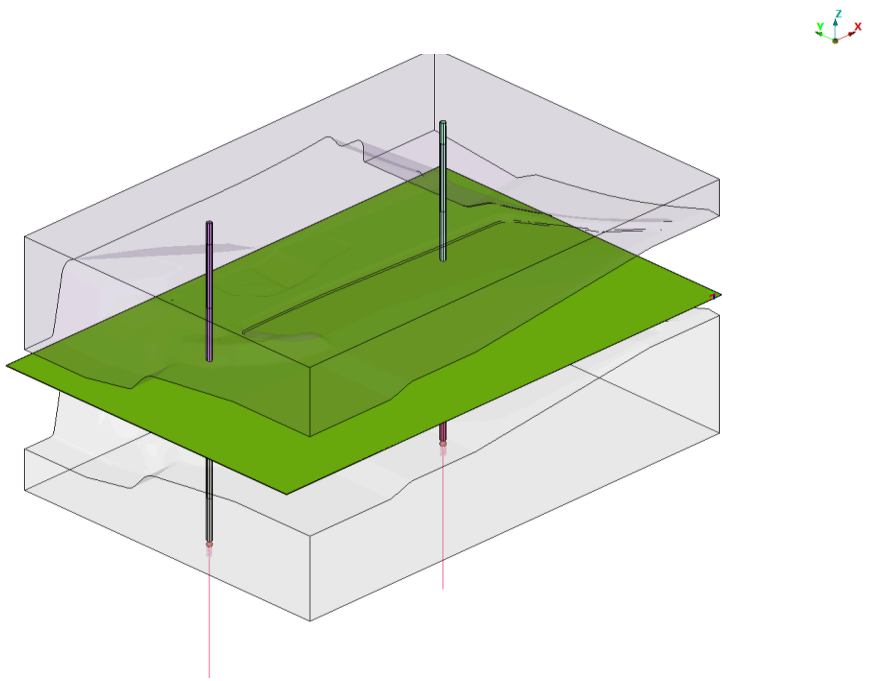
Currently in last phase of project

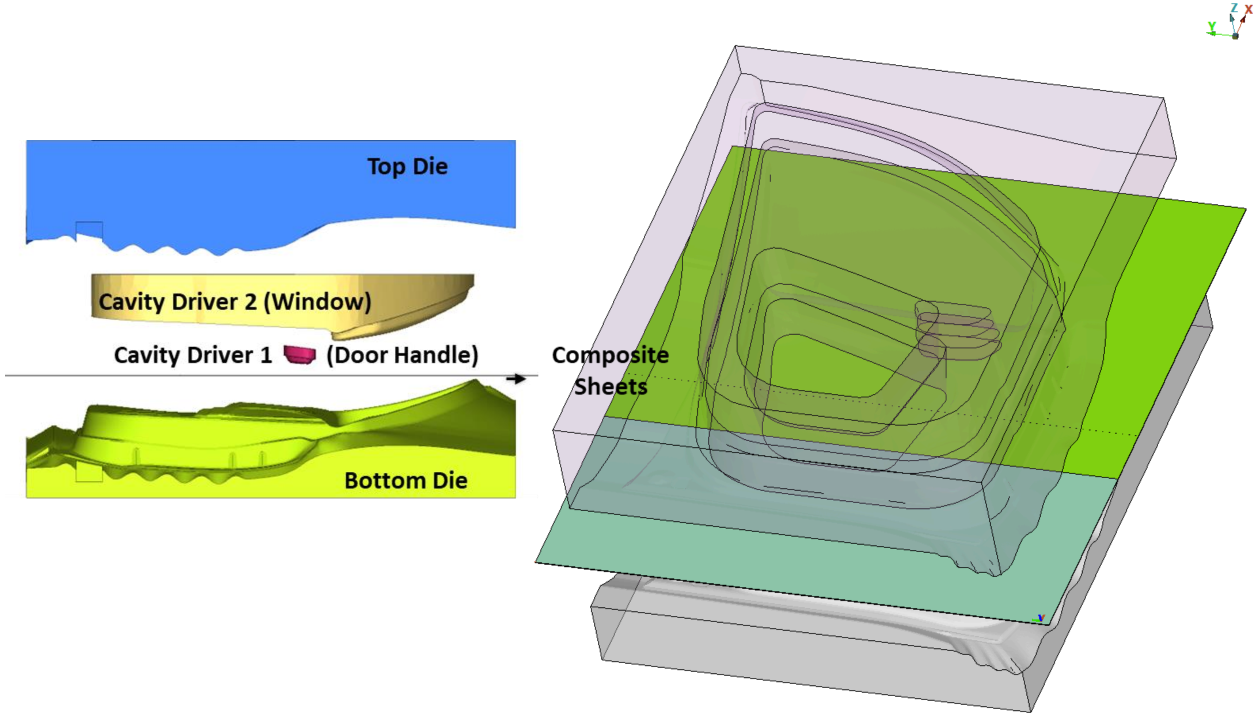
Testing

SOP's for static and dynamic tests to be finalized by OEM

Progress: Manufacturing Simulations

Inner Beltline Stiffener	Inner Panel



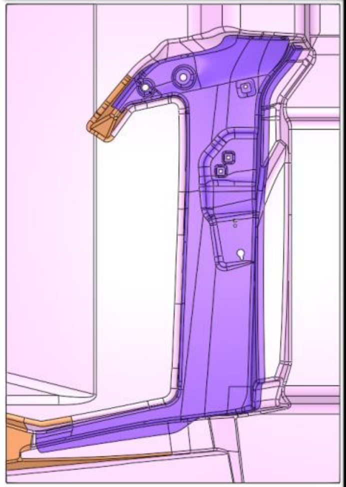


- Final manufacturing simulations were run on inner beltline stiffener tool.
- Location of pins is being investigated before manufacturing starts.

- Window, sash formation through use of cavity driver
- Door handle region formation through use of a smaller cavity driver
- Adjustable slots to vary material holding locations
- A simple A-frame with needle gripers is being considered

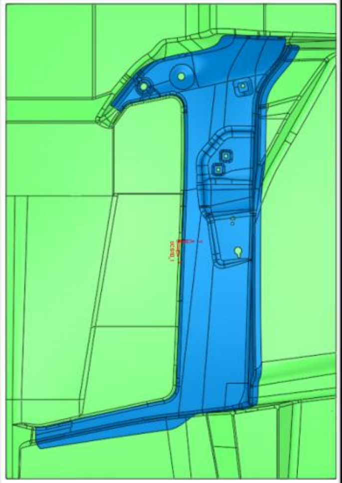
Progress: Inner Belt Line Stiffener Tooling

Concept A



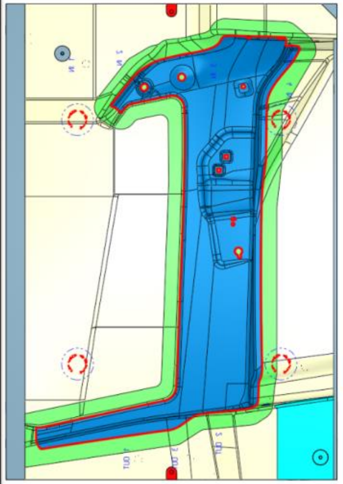
- This version shows early changes (tan) to trouble spots in shutoff as determined by Lanxess simulations.

Concept B



- Various Simulations at Lanxess helped determine additional trouble spots in the parting line as well as the part itself. These kinks were worked out through a series of concept designs. Concept B is an intermediate design.

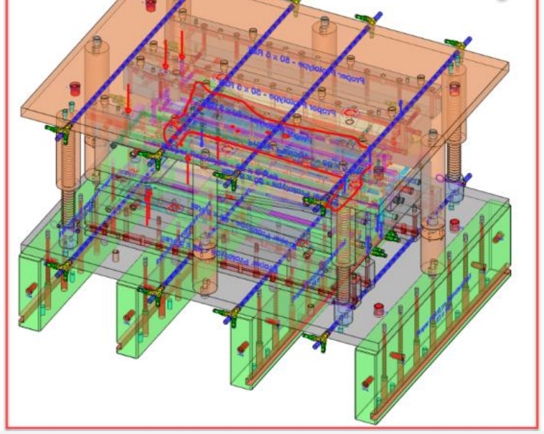
Final Design

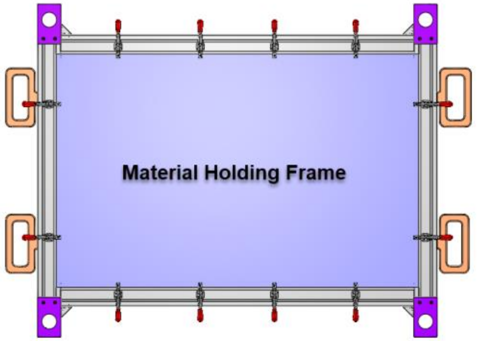


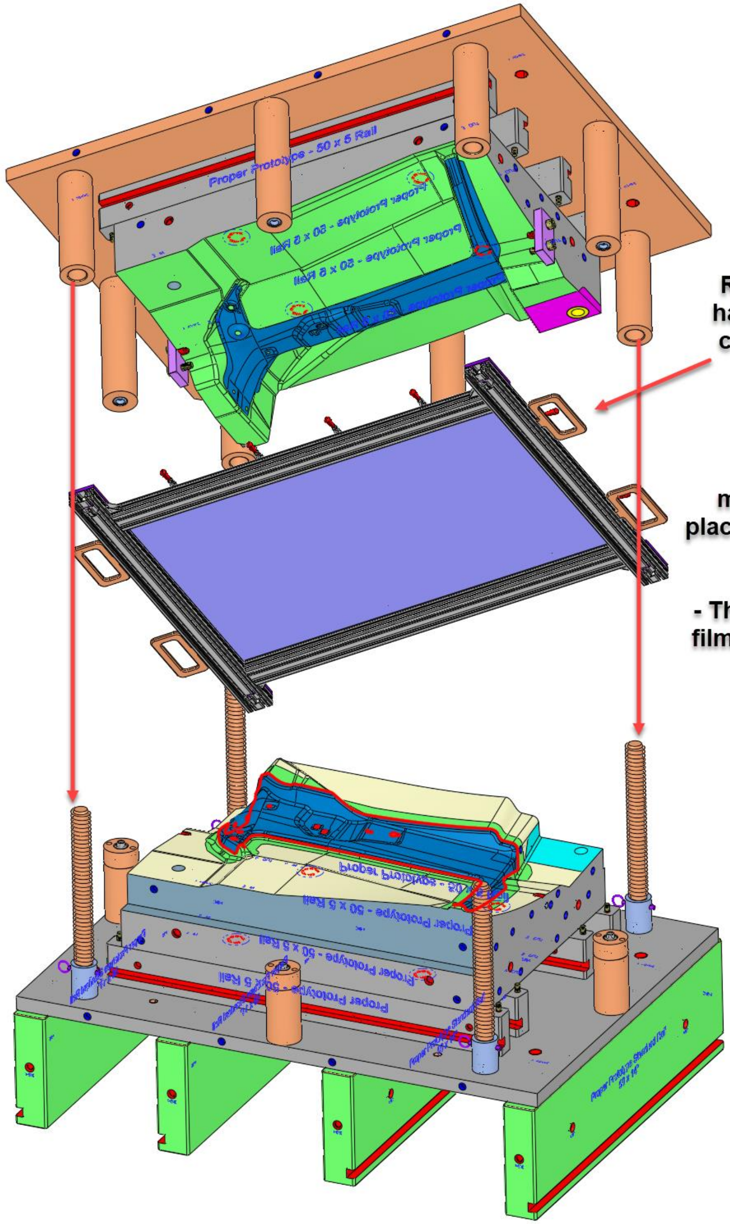
- The final design has all changes added as a result of simulation results.

- Clearance cut into edges as needed, to give room to the frame and any clamps holding material in place.

Final Tool Design







Removable handles stay cool during heating

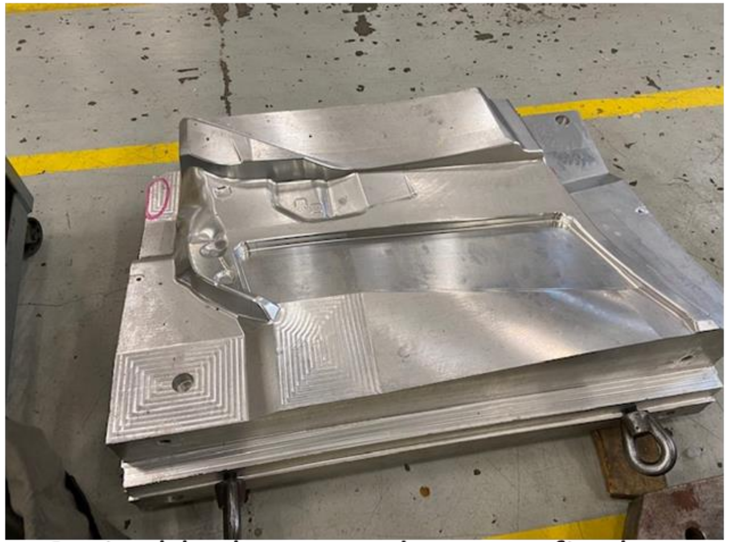
- The hot frame + molten sheet is maneuvered over to the lower half and placed onto pegs where it's held suspended over the tool with springs.

- The upper half of the tool closes onto the film, pushing the film and connected frame into the lower half as it closes.

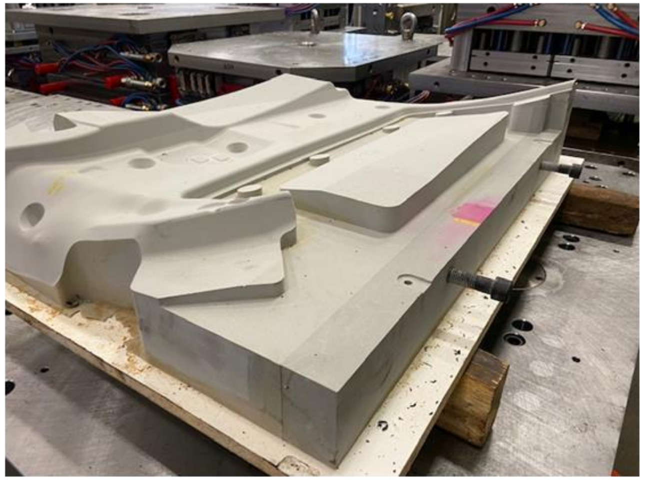
Progress: Inner Belt Line Stiffener Tooling

Doe Belt Line Reinforcement

Core block prepped to start final assy.

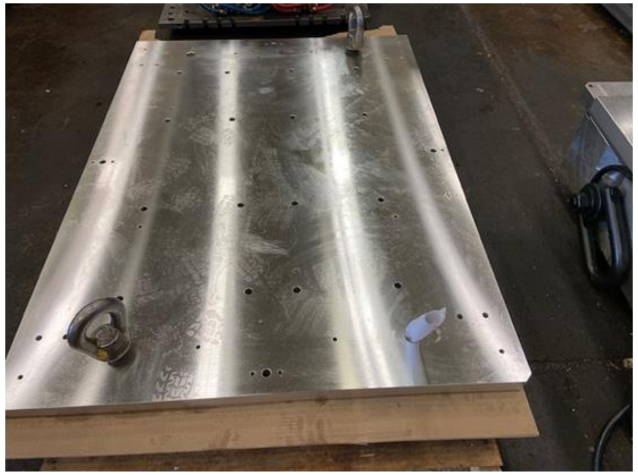


Cavity block prepped to start final assy.

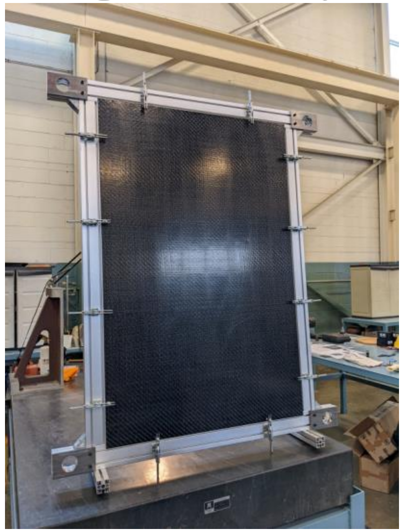


Routering fixture completed

Spacer block and rails for final assy.



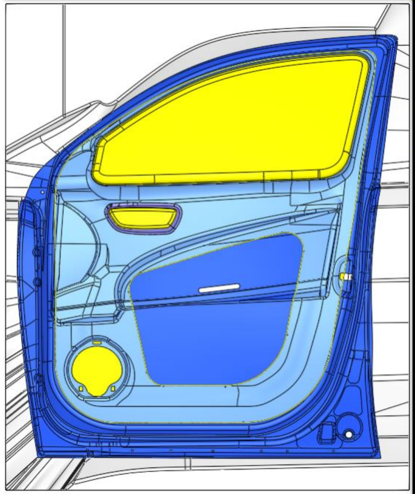
Core and cavity clamp plates for final assy.



Material Holding Frame

Progress: Inner Panel Tooling

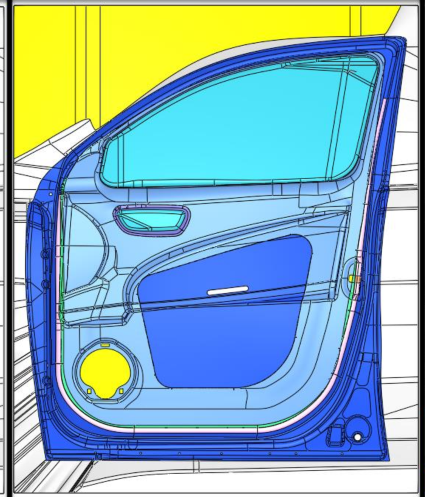
Concept A



- Early concept used to run initial simulations and build final design off of.

- Original driver parting lines were tweaked in later designs based on material simulation as well as machining requirements.

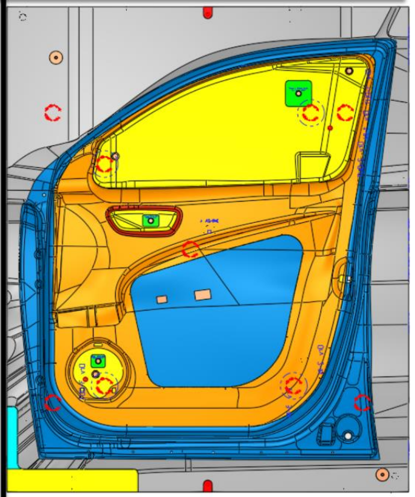
Concept C



- Parting lines and draft on both drivers were improved after simulations.

- Parting lines in the part openings were changed to reduce material stress.

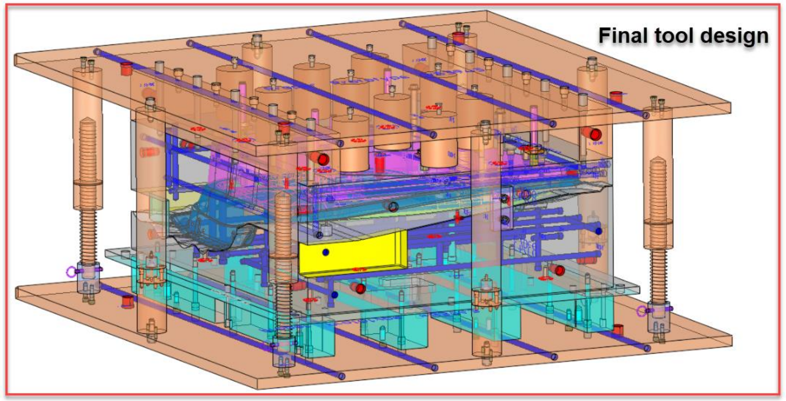
Final Design



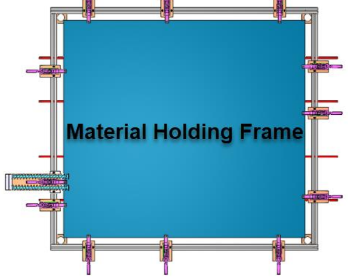
- Drivers finalized, with proper draft, cleaner parting lines, and standoffs for shipping added.

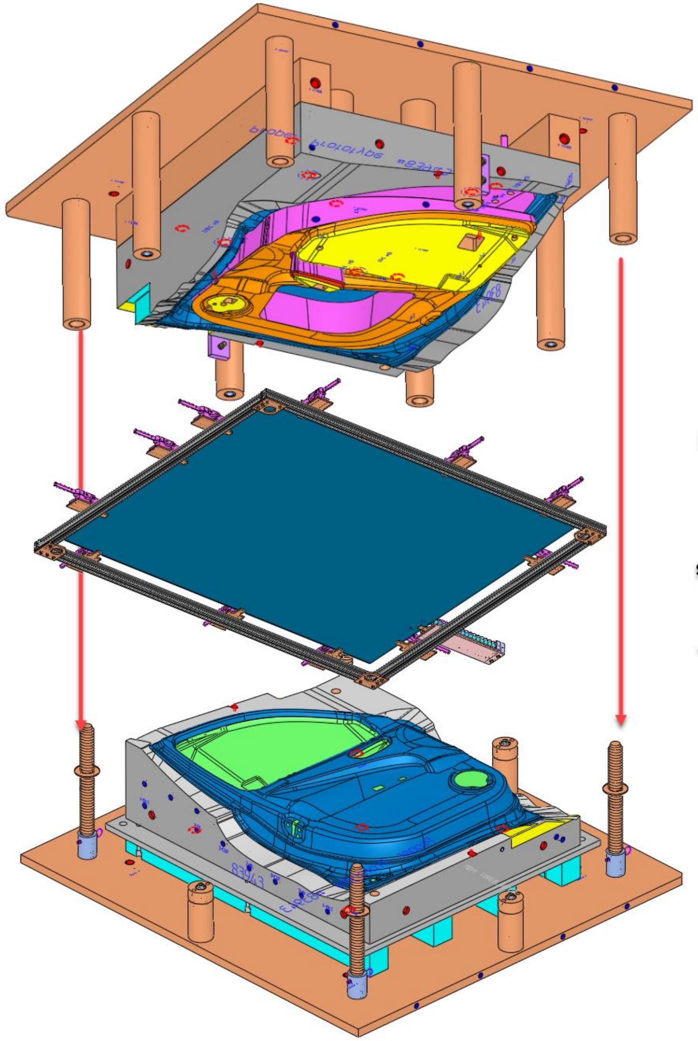
- Clearance cut into edges to make room for clamps that hold the material in place during forming.

- Parting lines in both openings and part exterior were further developed to help form with the least stress and tension possible.



Final tool design





- Gravity and gas springs push drivers forward as upper half is lifted.

- The hot frame + molten sheet is maneuvered over to the lower half and placed onto pegs where it's held suspended over the tool with springs.

- The upper half of the tool closes onto the film, with the small driver touching the film slightly ahead of the larger driver, and finally the rest of the upper half.

- The tool continues to close, with the pillars on the upper half pushing down on the frame, moving the entire frame at the same rate as the tool closure.

Progress: Inner Panel Tooling

Doe Door Inner Reinforcement

Core block in final assy.

Core block in final assy.

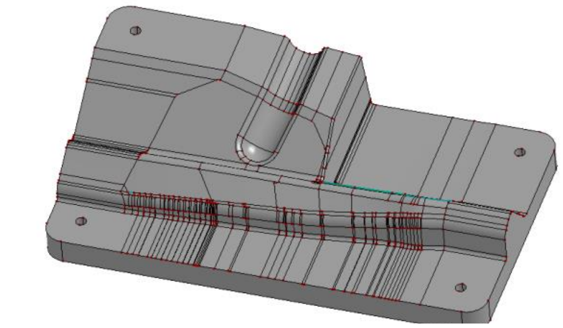
Routering fixture completed

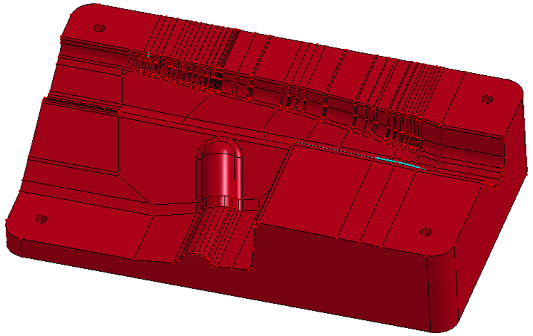
Core clamp plate in final assy.

Cavity clamp plate in final assy.

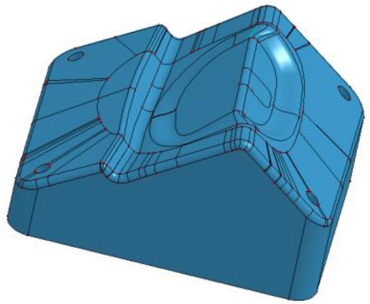
Progress: Metal Stamped Parts

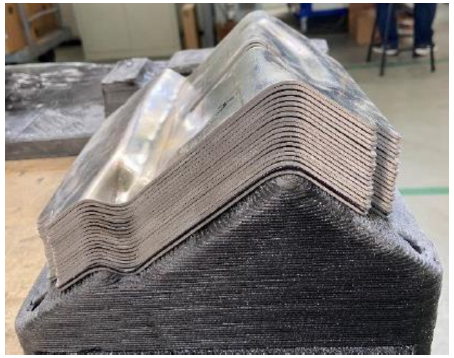
Tooling for Anti-Intrusion Beam





Crash Form Tooling for Bracket B

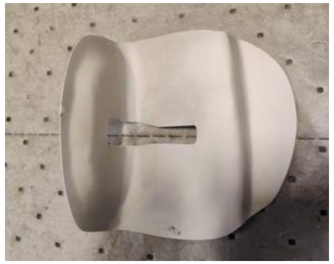




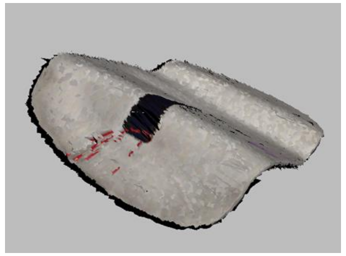
- Crash and draw forming tooling made from 3D printing (CF + Nylon 12) with concrete backfill
- Tool design finalized and print proceeding
- 20 blanks of 1.2 mm mild steel cut and formed

Progress: Metal Stamped Parts Validation

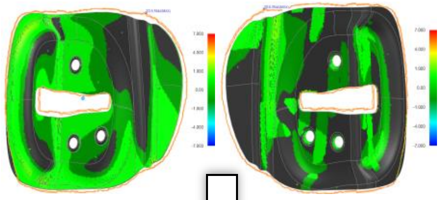
Coating the Parts for 3D scanning



Scanning And Modeling In Artec Studio

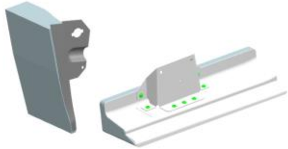


Comparing CAD with Scans

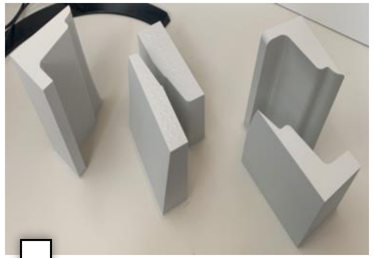


Check Fit with Inner Panel CAD

Cut Section CADs of Inner Panel with required contours



3D printing inner panel sections



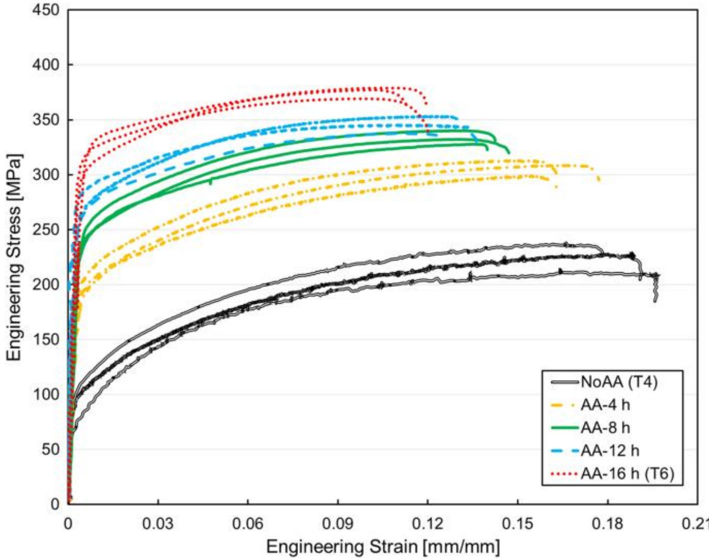
Comparing fit with 3D printed parts

Key Observations:

- Significant deviations observed in overhanging parts
- Bend radii and bend angles' mismatch observed at certain locations likely due to spring-back
- Minor deviations can be fixed through hand working the sheet metal part

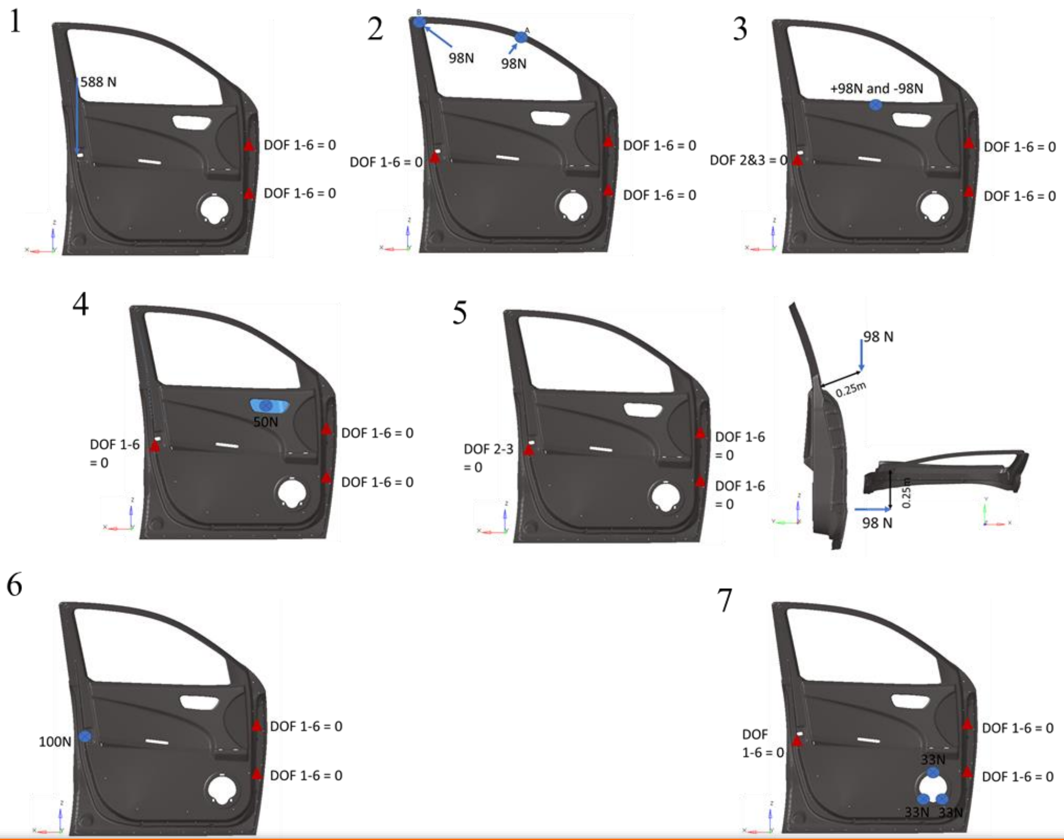
Solutions:

- Higher yield strength of Al 6061-T6 is the cause of excessive spring-back.
- Will anneal formed parts to reduce yield strength and restrike using same tools
- If unsuccessful, press brake and hand work will be sufficient to make formed components conform



Progress: Static Performance

- The linear static load cases represent door performance for daily use and occasional misuse
- The composite design optimization is carried out for the listed static load cases.
- All static load cases are well satisfied for the composite door.



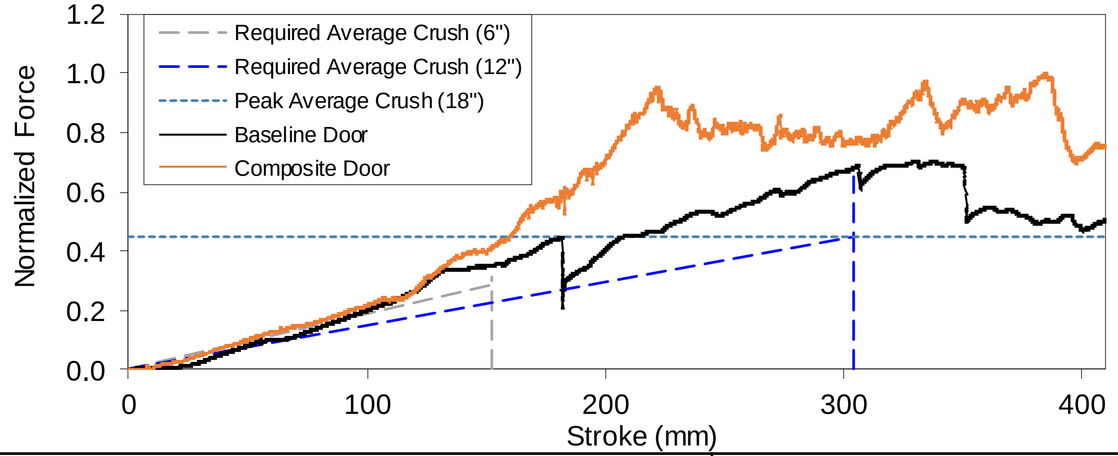
S No.	Target category Subcase		Composite door response
A	Mass Target (% mass savings)		
1		Structural frame mass	45%
2		Total mass	32%
B	Frame Related (% stiffness increase)		
1		Door Sag - Fully open	32%
2a		Sash Rigidity at point A	10%
2b		Sash Rigidity at point B	55%
3		Beltline stiffness-Inner panel	79%
4		Window regulator (Normal)	69%
5a		Mirror Mount rigidity in X	1%
5b		Mirror Mount rigidity in Y	67%
6		Door Over opening	1%
7		Speaker mount stiffness	48%
8		Outer panel stiffness	80%

The prototype composite door satisfy all static load cases
with more stringent target definitions set by the OEM partner.

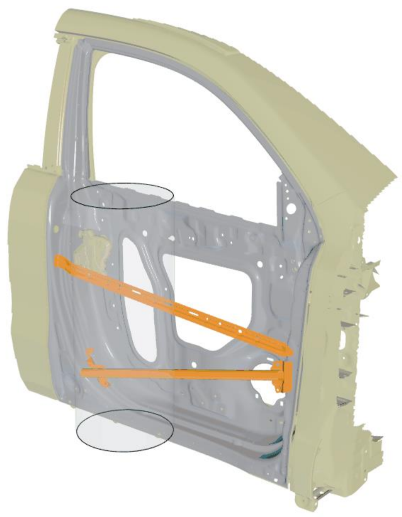
Progress: Structural Performance

FMVSS 214 S Quasi-static Pole test

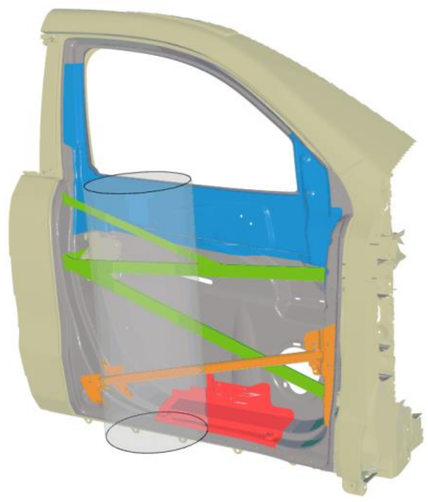
- A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.



FMVSS214 S OEM Requirements	Composite door response (% Improved)
Initial Average Crush	23%
Intermediate Average Crush	104%
Peak Crush	124%



Baseline steel door



Composite door

The average crush resistance of composite door is significantly higher than the OEM requirements for QSP test.

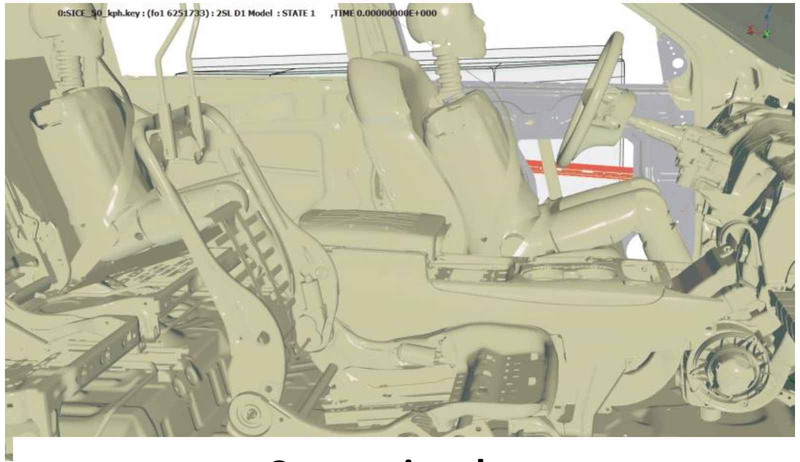
Progress: Structural Performance

IIHS Side Impact moving deformable barrier test

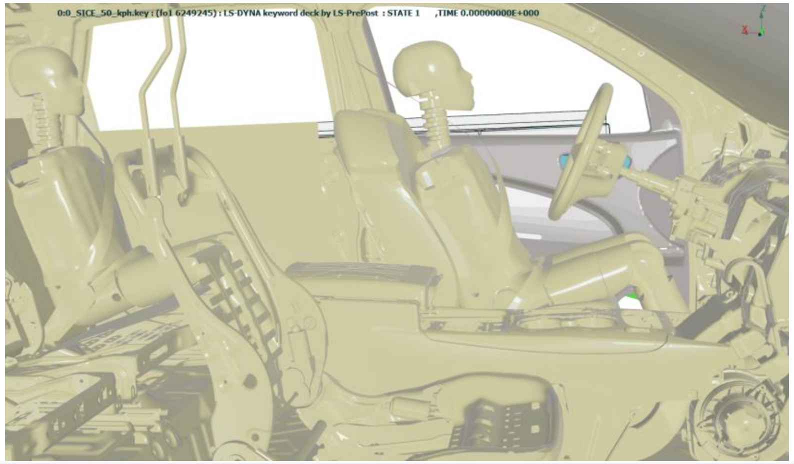
- A moving deformable barrier of mass 1500 kg is impacted with a stationary vehicle at 50 km/h.
- A 5th percentile female SID IIs dummy is included in the test as per NCAP guidelines.
- A gauging metrics for IIHS SI- MDB is defined
  - Success (Green) – If intrusion is below baseline target values (<b)
  - Tolerable (Yellow) - If intrusion is more than baseline values but smaller than 10 % difference (>b, <b+10%)
  - Failure (Red) – If intrusion is 10% above baseline value (>b+10%)
- No exposed crack in the door interior.

Key Performance Indicator	Composite door response
Safety survival space	+4%
Max roof intrusion	- 4%
Max windowsill intrusion	-14%
Front door dummy hip intrusion	-22%
Max door lower intrusion	-1.5%

Baseline steel door



Composite door



The composite door outperforms baseline door for IIHS MDB test with No exposed crack.

Progress: Testing Overview

Composite Door Assembly-level Tests

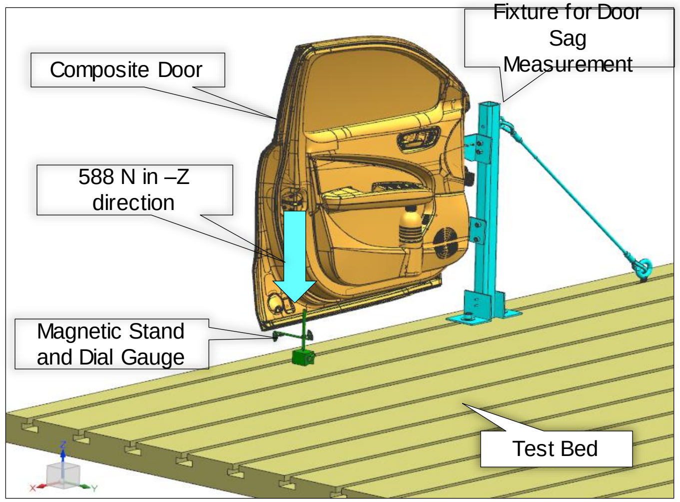
- Static Testing
  - Door Assembly Sag
  - Door Assembly Sash Rigidity
- Dynamic Testing
  - FMVSS 214
  - IISH SI MDB(DB)
- NVH Evaluation
  - Experimental Modal Analysis

Progress: Static Testing

Static Load Case 1: Door Sag

Test Setup:

- Test bed (slotted table available at CU-ICAR) to be utilized.
- In-house fabricated fixture for supporting the door.
- Supports at the hinge locations on A-pillar



Static Testing Setup as designed for Door Sag evaluation

Test performed at various opening angles-
- fully open (68 deg.)
- Angle such that door latch and striker distance is 150 mm

Loading Condition:

- 588 N load applied in – Z direction @ Door Latch point
- Load applied using overhead crane, chain hoist and pulley setup on the test bed
- Force gauge (100 kgf. capacity) to be utilized to measure the load applied

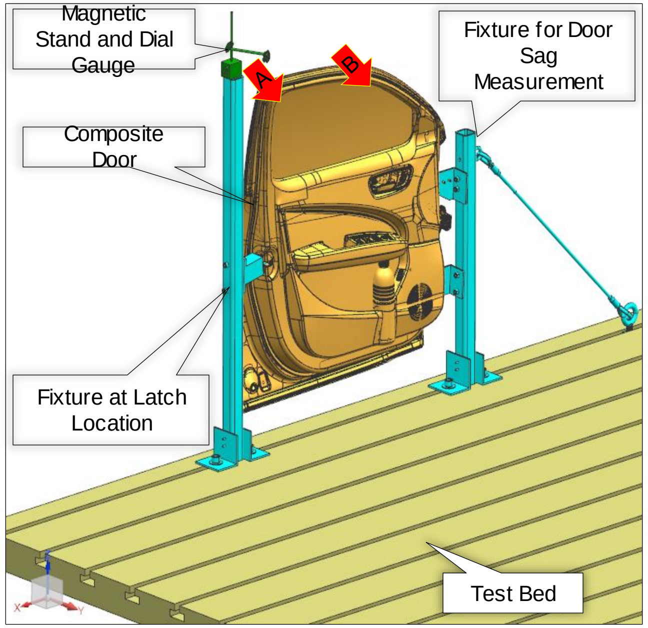
Measurement:

- Displacement @ lower B-pillar corner of the door
- Displacement measured using dial gauge mounted on magnetic stand

Static Load Case 2: Sash Rigidity

Test Setup:

- Test bed (slotted table available at CU-ICAR) to be utilized.
- In-house fabricated fixture for supporting the door.
- Supports at the hinge locations on A-pillar and at the latch near the B-pillar



Static Testing Setup as designed for Door Sash Rigidity evaluation

Loading Condition:

- 98 N load applied in direction perpendicular to the door sash @ locations A and B respectively
- Force gauge (100 kgf capacity) to be utilized to measure the load applied

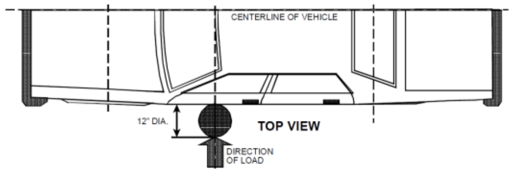
Measurement:

- Displacement @ upper B-pillar corner of the door
- Displacement measured using dial gauge mounted on magnetic stand

Current Status : In-house fixture in design release and fabrication stage

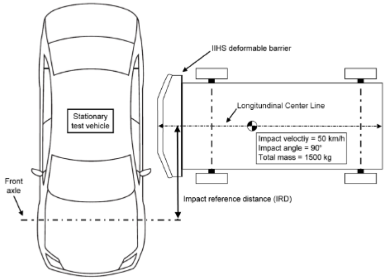
Progress: Dynamic Testing

1. FMVSS 214s (Quasi-static pole test)



A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.

3. IISH SI MDB(DB)



A moving deformable barrier is impacted with a stationary vehicle at 50 km/h.

1. FMVSS 214s (static)
   - Load Application Location: Vertical midline of door
   - Deflection: 6", 12", and 18" toward interior
   - Measurement: Force required for prescribed deflections
   - Equipment Used: Linear potentiometers, load cells, hydraulic cylinder
2. IISH SI MDB(DB)
   - Load Application Location: 160.8 cm from front axle, perpendicular to target vehicle
   - Load: 1500 kg barrier @ 50 km/h
   - Measurement: Interior intrusion profile, door acceleration
   - Equipment Used: Moving Deformable Barrier (MDB), accelerometers, instrumented dummies

Progress: Manufacturing

- **Inner Beltline Stiffener**
  - Final assembly and mold function testing is pending
  - Material handling frame 100% complete
  - Tryout scheduling in week of May 16th

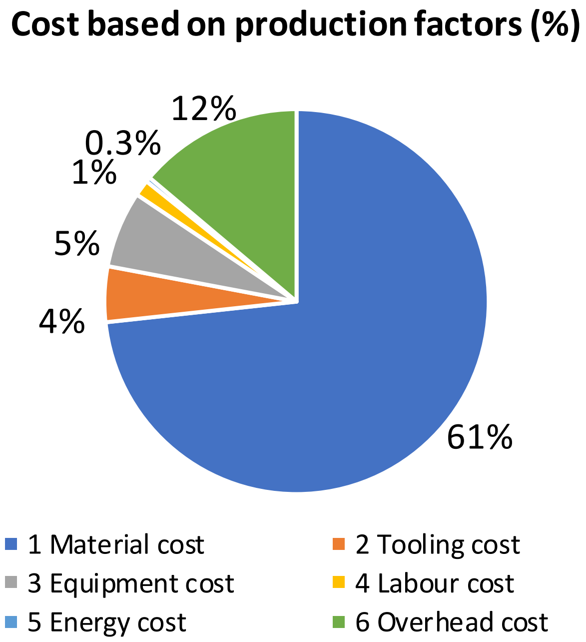
- **Inner Panel**
  - Mold 95 % complete doing final assembly and mold function testing
  - Material handling frame 80% complete
  - Tryout scheduling in week of May 30th

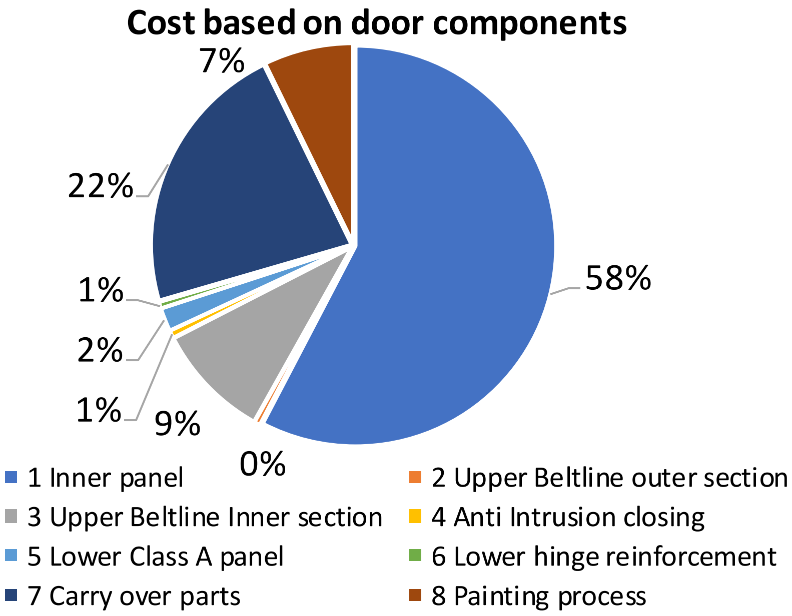
Progress: Cost Modelling

Parametric cost model assumptions:

- Production volume per year – 20,000
- Workers per machine – 4
- Overhead rate (18 ~ 24% of total cost)
- Cost of carry over parts is constant (~ $180)
- Cost of carbon fiber > **$ 7/lb**

Parts	Baseline Weight (kg)	Current Composite Design	
		% Mass reduction	$$/lb. saved
Structural parts	15.44	45%	4.44
Non-structural parts	9.37	47%	4.18
Carry Over Parts	6.29	0%	0
Painting			
Total	**31.1**	**32%**	**5.84**





Identified parameters	Identified Variations	Total Cost ($)
Electricity cost per kWh(cents)	7.5~17	813 ~954
Scrap rate(%)	4~15	
Mold life(years)	6~11	
Equipment life(years)	5~13	
labor wage($)	15~28	
Material cost per kg ($)	105~119	

Cost Modelling: Glass vs Carbon

	Carbon fiber door	LCCF Door (Oakridge)	Glass fiber door
Light-weighting	32 %	32 %	>25 %
Static Performance	Excellent	NA	Satisfactory (Validated MAT card used)
Dynamic Performance (QSP test)	Excellent	NA	Excellent (Validated MAT card used)
Cost of Inner Panel	**$ 570**	**$ 494**	**$ 74**
Total Cost of door (with parts consolidation)	**$ 928**	**$ 842**	**$ 352**
Target cost increase per lb. saved	**$ 3.76**	**$ 3.76**	**$ 2.94**
Achieved Cost increase per lb. saved	**$ 5.84**	**$ 1.92**	**0**

- ❑ Cost of carbon fiber is > $ 7/lb.
- ❑ Low cost carbon fiber is $ 4.75 /lb
- ❑ Glass fiber cost < Cost of carbon fiber

The Current door design is optimized for Carbon fiber material. If optimized for Glass Fiber – almost 25% of weight savings could be achieved at approximately same cost as baseline steel door which successfully meets design requirements.

Remaining Challenges & Barriers

1. COVID 19

1) Talks with our tooling partners began August 2019. Tooling only began in May 2021

2) Currently Tooling is completed and being prepped for prototyping trials.

2. Manufacturing

1) The team understands the challenges and barriers involved in manufacturing and assembly and is working tirelessly to chart to overcome these.

2) The team hopes to leverage experience gained from the manufacture & assembly of our previous low-cost prototype door.

3. Cost

1) The high cost of carbon fiber remains a barrier for cost targets.

2) Glass fiber woven composite door met most static targets.

	CF	GF
Lightweighting	32 %	>25%
Material cost	X	1/10 x
Overall door cost	$ 928	$ 352
$/lb increase	$ 5.8	$ 0

Collaborations

Key Organizations	Role	Responsibilities
CLEMSON UNIVERSITY	Principal investigator	• Project management • Design development • Linear & NVH analysis • Cost & factory modeling • Discontinuous fiber material characterization
UNIVERSITY OF DELAWARE	Co - PI	• Non-Linear analysis • Continuous fiber (UD and Woven) material characterization • Design support
HONDA The Power of Dreams	OEM Partner	• Target definitions • Student mentoring • Computation support for running complex simulations • Component & vehicle crash testing
LANXESS Energizing Chemistry	Material Partner	• Material Supplier • Manufacturing Simulation Support
Proper Group INTERNATIONAL Advanced Engineering • Superior Technology	Tooling & Prototyping Partner	• Manufacturing/tooling design & simulation • Prototyping

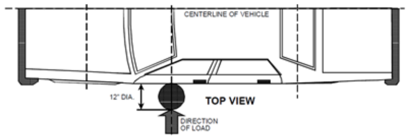
Proposed Future Work

Manufacturing

- Prototyping location is prepped and blocked off for trials
- Initial manufacturing trials for inner panel and inner beltline stiffener to be held starting May.

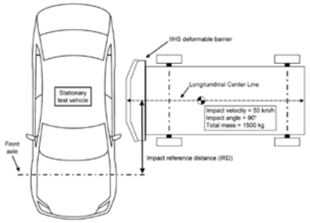
Testing

1. FMVSS 214s (Quasi-static pole test)



A cylindrical barrier is used to deform the door for 18 inches under quasi static loading condition.

3. IISH SI MDB(DB)



A moving deformable barrier is impacted with a stationary vehicle at 50 km/h.

Test	Composite Door Trials	Steel Baseline Trials
FMVSS 214s	2	-
OEM Test	2-3	2-3
IISH SI MDB	1	-

- Tests scheduled in August 2022

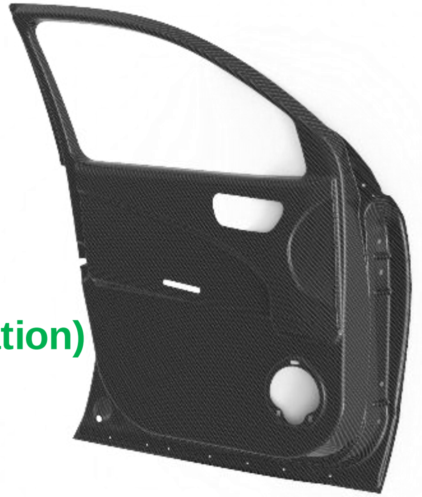
*Any proposed future work is subject to change based on funding levels

Summary

Baseline Door

Structural Parts	**17 Parts**
Structural Mass	**15.44 kg**
Total Parts	**61**
Total Mass	**31.1 kg**
Trim + Glazing	**3.7 kg + 3.49 kg**
Performance	**5 star**
Costs ($/lbs saved)	**NA**

Ultralightweight Composites Door



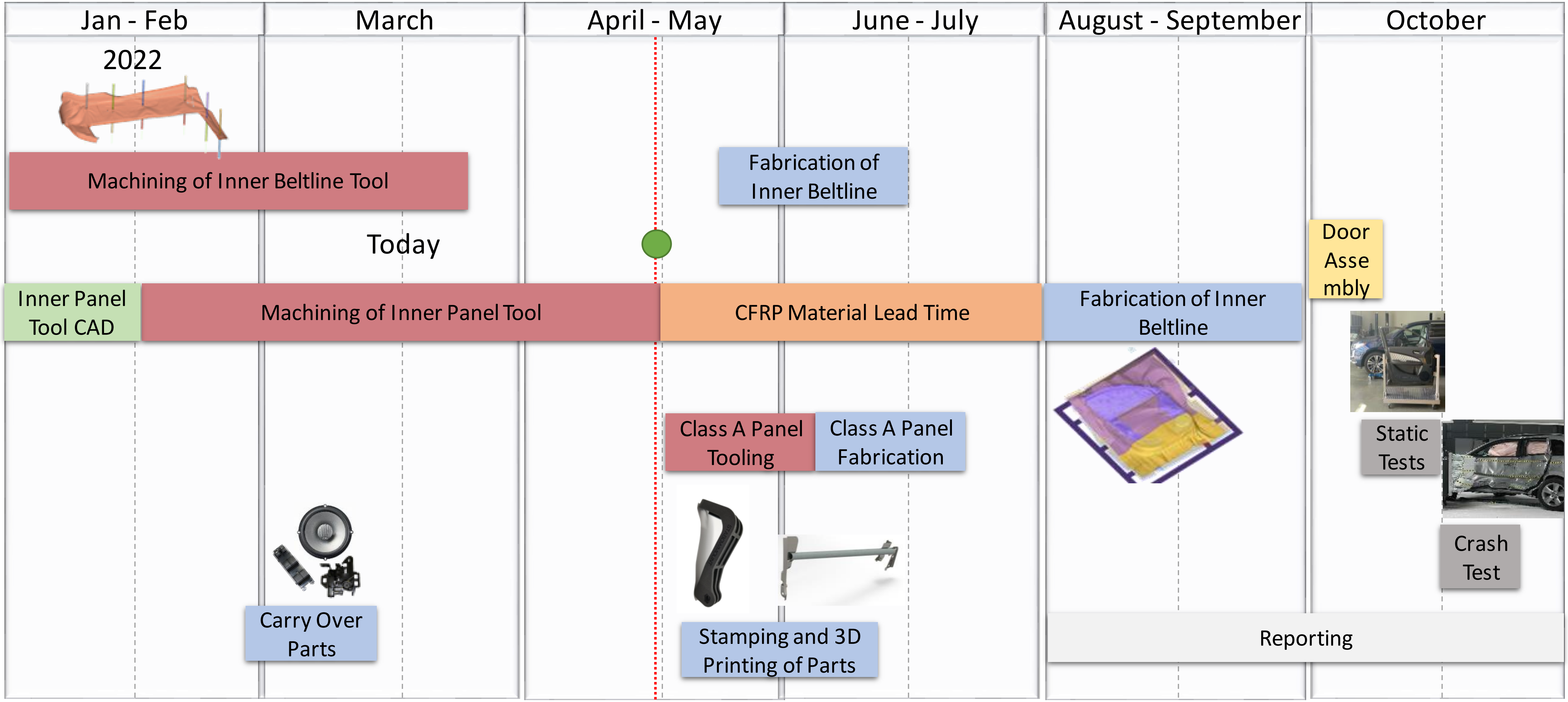
Structural Parts	**6 Parts**
Structural Mass	**8.4 kg**
Total Parts	**52**
Total Mass	**21.1 kg**
Trim + Glazing	**2.59 kg + 1.34 kg**
Performance	**Meets or exceeds (Simulation)**
Costs ($/lbs saved)	**$ 5.8 ($ 5 permitted)** **$ 1.92 (LCCF Door)**

- Tooling completed for Inner Beltline Stiffener and Inner Panel
- FEA showed the composite door exceeding static and crash targets.
- Manufacturing trials scheduled in May 2022
- Crash tests scheduled in September 2022
- Cost analysis was updated.

2020 Technology Integration Award for Clemson Composites Center

Technical Back Up Slides

Progress: Timeline



Design and Simulation | Tooling | Fabrication | Assembly | Testing